

**ASCAC Methods  
Development Peer  
Review**

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# Simultaneous Aerodynamic and Structural Design Optimization (SASDO) of a 3-D Wing

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# Ultra-Efficient Engine Technology

Propulsion Airframe Integration Project (2000-2002)

**Goal: Reduce aircraft CO<sub>2</sub> emissions by developing advanced technologies to yield lower drag propulsion system integration for a wide range of vehicle classes**

Conventional Configuration



Revolutionary Configuration



## Enable Ultra High Bypass Ratio Engine Integration

- Advanced CFD design methods
- Active Shape Control Variable Area Nozzle
- Active Shape Control Variable Radius Nacelle Leading Edge

## Enable Boundary Layer Ingestion S-inlet Nacelle Integration

- Advanced CFD design methods
- Active Flow Control S-inlets
- Active Flow Control boundary layer reenergization

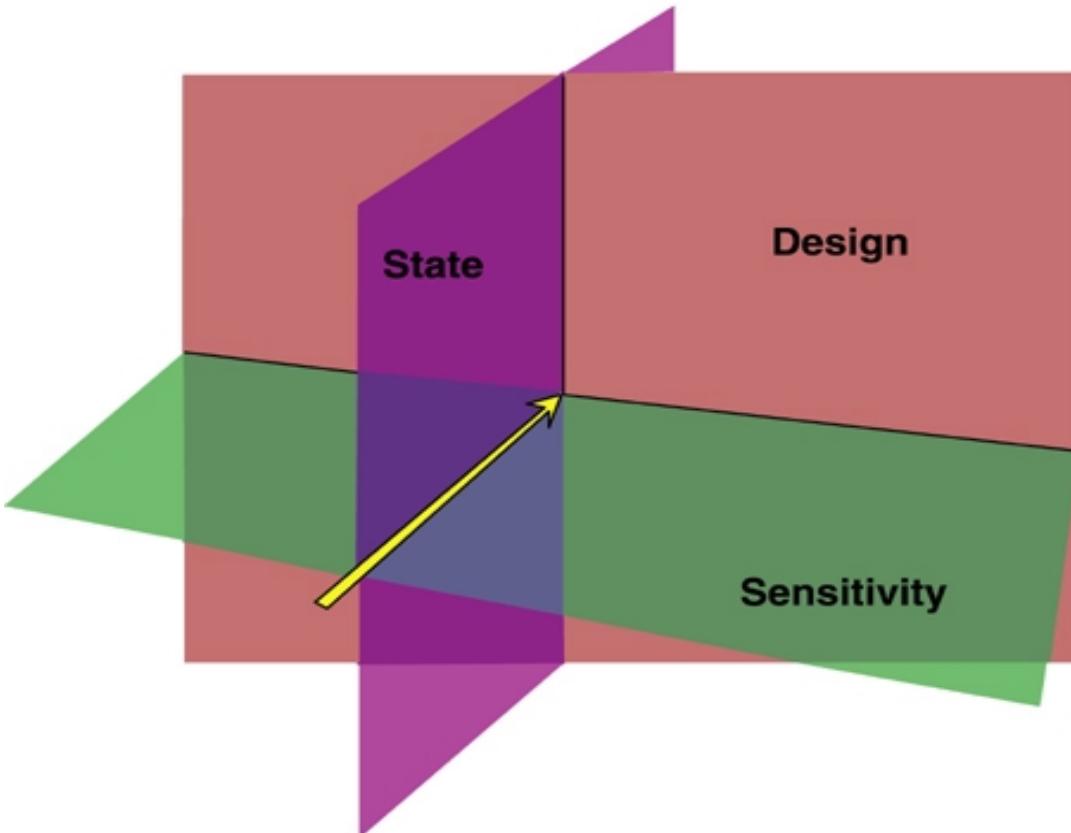
# Motivation

- Develop MDO algorithm for high fidelity (nonlinear) aerodynamic/structural analysis
  - Loosely coupled discipline interactions
  - Validated legacy codes
  - Minimize implementation issues
- Reduce computation cost from conventional optimization

# Outline

- Conventional Approach
- Optimization Challenges
- SASDO Approach
- Process Implementation
- Application Problems
- Results
- Conclusions

# Conventional Approach



$$\min_{\beta} F(Q, u, X, \beta)$$

**subject to constraints**

$$g_i(Q, u, X, \beta) \leq 0, i = 1, 2, \dots, m$$

$\beta$  design variables

X computational mesh

Q flow field variables

u deformation field variables

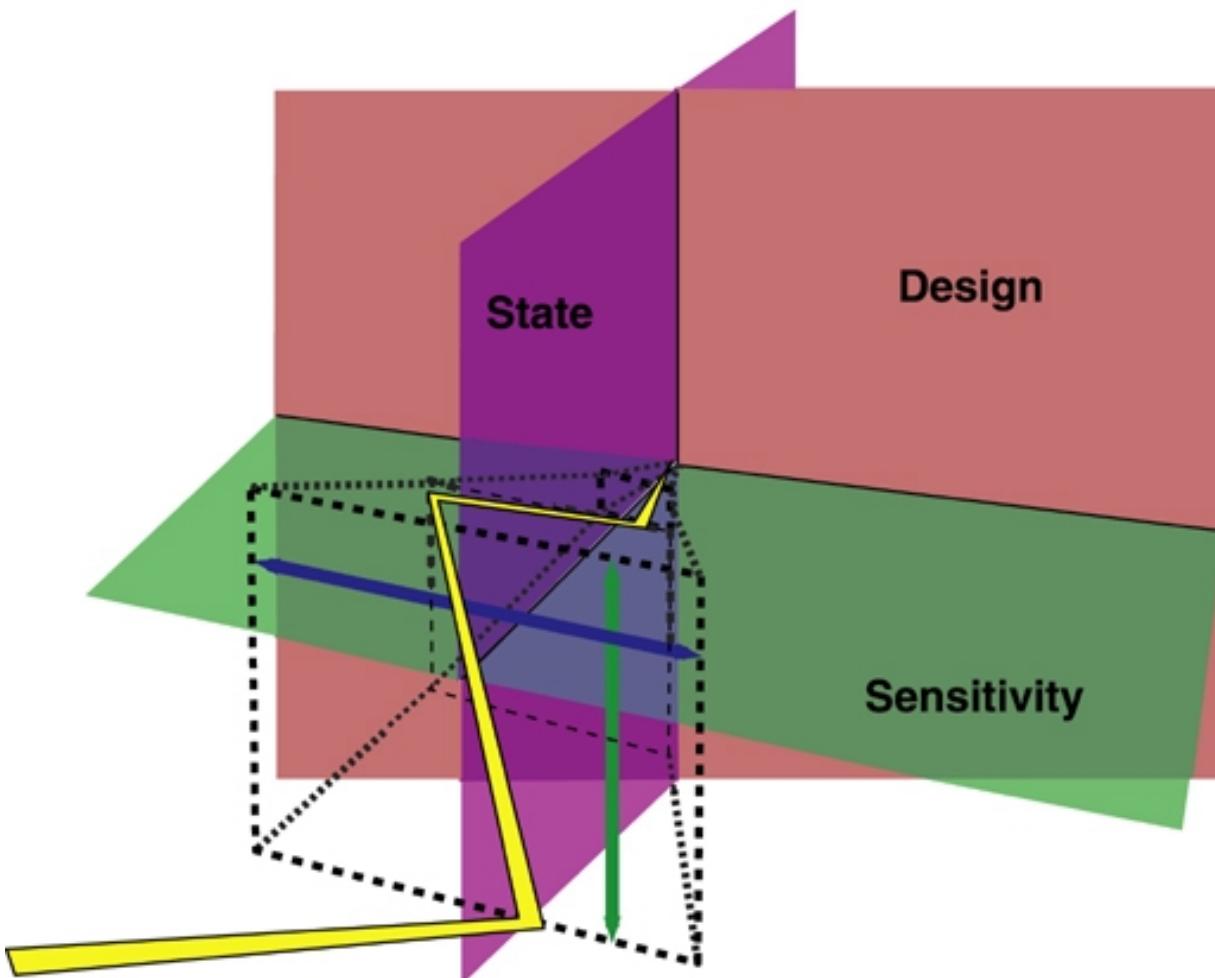
$Q \quad \} \quad$  solutions of coupled  
 $u \quad \} \quad$  aero-struct equations

$Q' \quad \} \quad$  solutions of coupled  
 $u' \quad \} \quad$  sensitivity equations

# Optimization Challenges

- Why SASDO?
  - Reduce the cost incurred by well-converged, iterative function and sensitivity analyses at non-optimal points in design space
  - Minimize modifications to discipline analysis codes
- How SASDO?
  - Interleaf optimization updates with iterative discipline and system analyses
  - Require better function and sensitivity convergence as optimization progresses

# SASDO Approach



$$\min_{\beta, Q, u} F(Q, u, X, \beta)$$

subject to constraints

$$g_i(Q, u, X, \beta) \leq 0, i=1, 2, \dots, m$$

and

$$R(Q, X, \beta) = 0$$

$$K(X, \beta)u - L(Q, X) = 0$$

# SASDO Approach

Partial convergence implies:

- Approximate functions (state) and gradients (sensitivities)
- Infeasibility in early steps

$$R(Q, X, \beta) \neq 0$$

$$K(X, \beta)u - L(Q, X) \neq 0$$

- Contributions to reduction of design variable domain

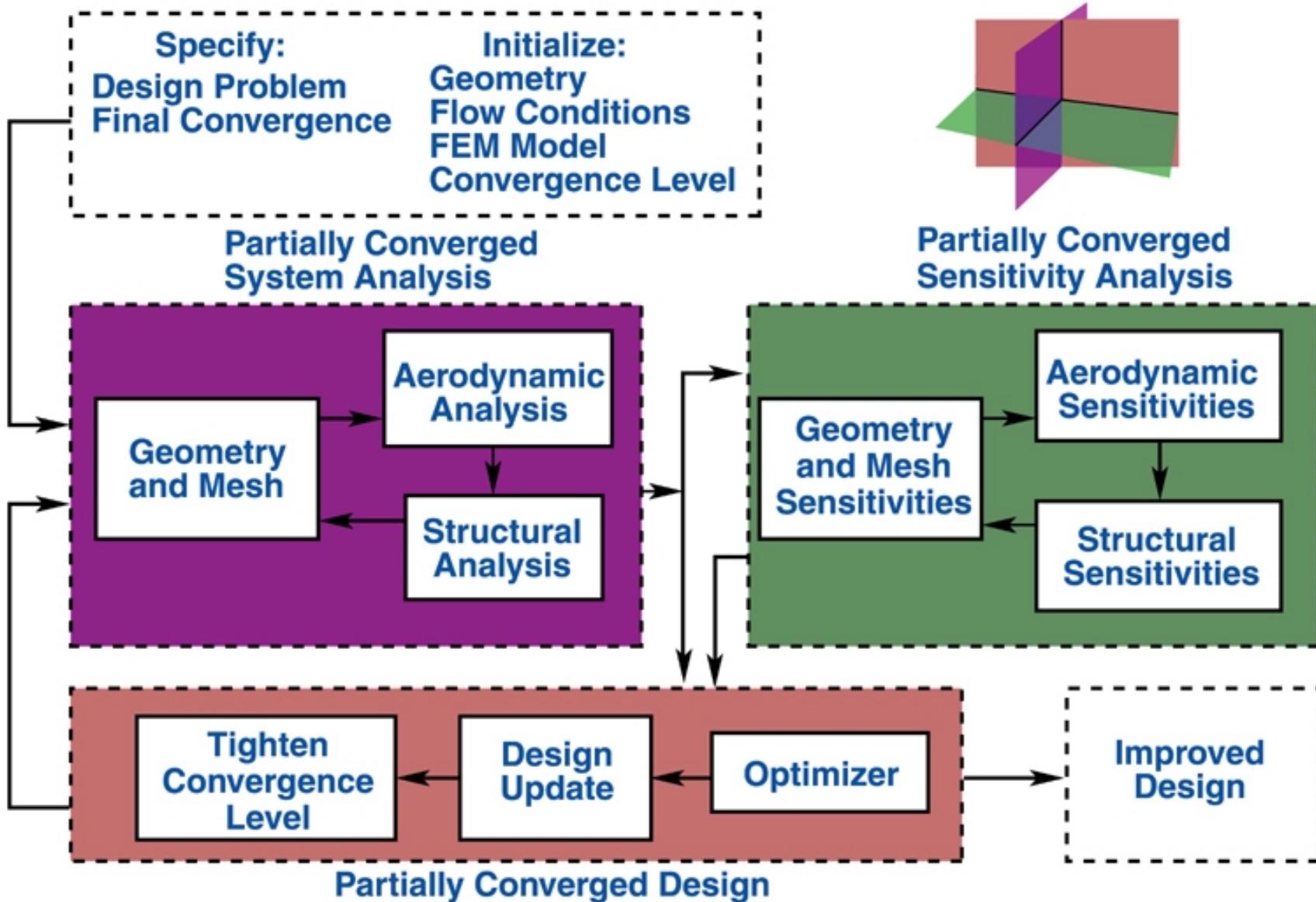
$$R + \frac{\partial R}{\partial Q} \Delta Q + \frac{\partial R}{\partial X} \Delta u + \left[ \frac{\partial R}{\partial X} X' + \frac{\partial R}{\partial \beta} \right] \Delta \beta = 0$$

$$Ku - L - \frac{\partial L}{\partial Q} \Delta Q + \left( K - \frac{\partial L}{\partial X} \right) \Delta u + \left[ \frac{\partial K}{\partial X} u - \frac{\partial L}{\partial X} \right] X' \Delta \beta + \frac{\partial K}{\partial \beta} \Delta \beta = 0$$

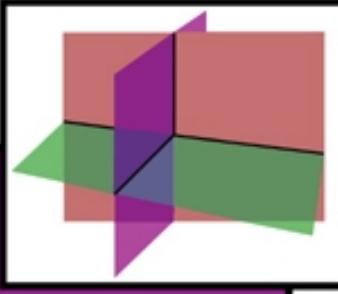
# **Summary of Earlier SAADO Development**

- Quasi 1-D Euler, nozzle design - 1993
  - 70% computational cost reduction
- 2-D Navier-Stokes, airfoil design – 1996
  - 40% computational cost reduction
- 3-D Euler, rigid wing design – 1999
  - 10-30% computational cost reduction
- 3-D Euler, flexible wing design – 2001
  - 10-30% computational cost reduction

# Process Implementation

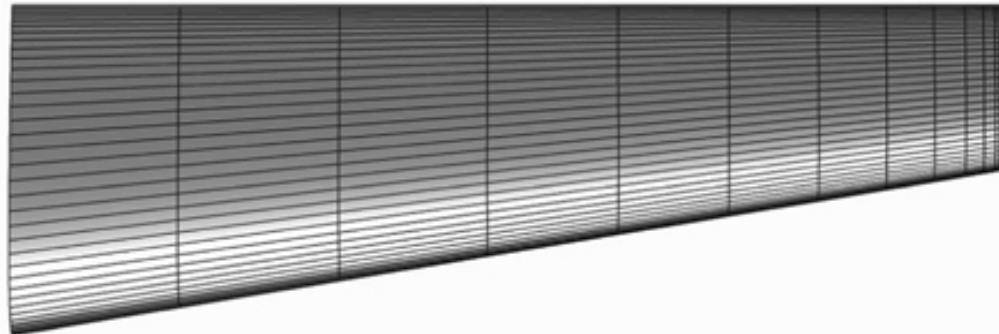


# Process Implementation Code Descriptions

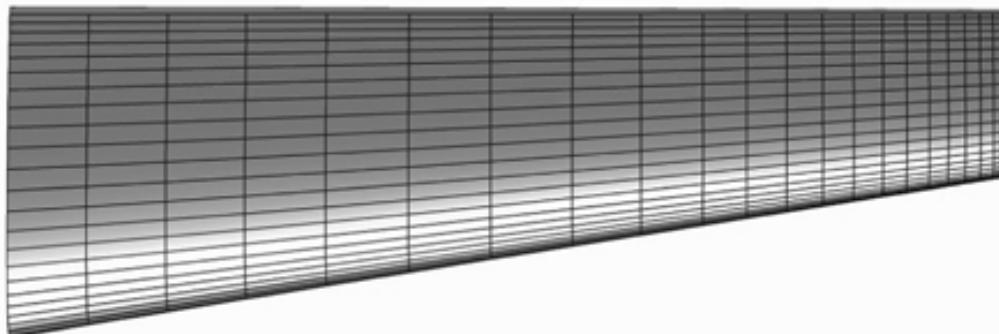
Code	Description	
RAPID	Surface geometry generation Rapid Aircraft Parameterization in Design	
CSCMDO	Volume mesh generation Transfinite interpolation of deformations	
CFL3D	General structured mesh Euler or Navier-Stokes flow analysis; Euler used in this study	
FEM	Finite Element Method linear structural analysis	
Sensitivity derivatives obtained by Automatic Differentiation of Disciplinary Analysis Codes		
DOT	Sequential Quadratic Programming (SQP), Vanderplaats R&D, Inc.	

# Process Implementation Computational Meshes

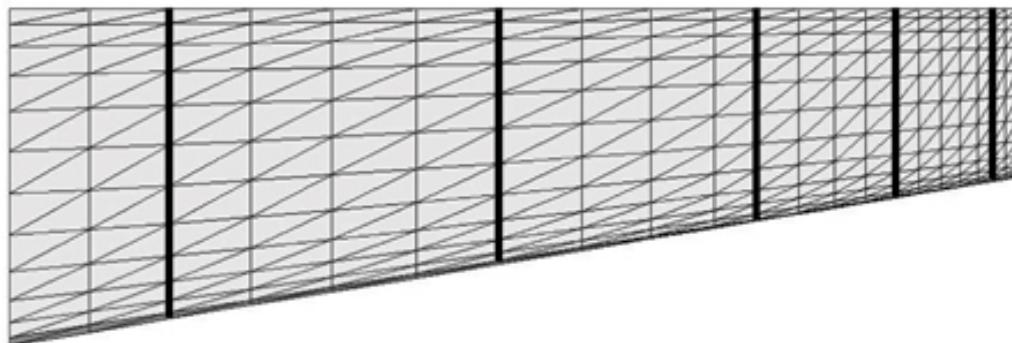
**97x17x25**  
**CFD mesh**  
**(rigid wing)**



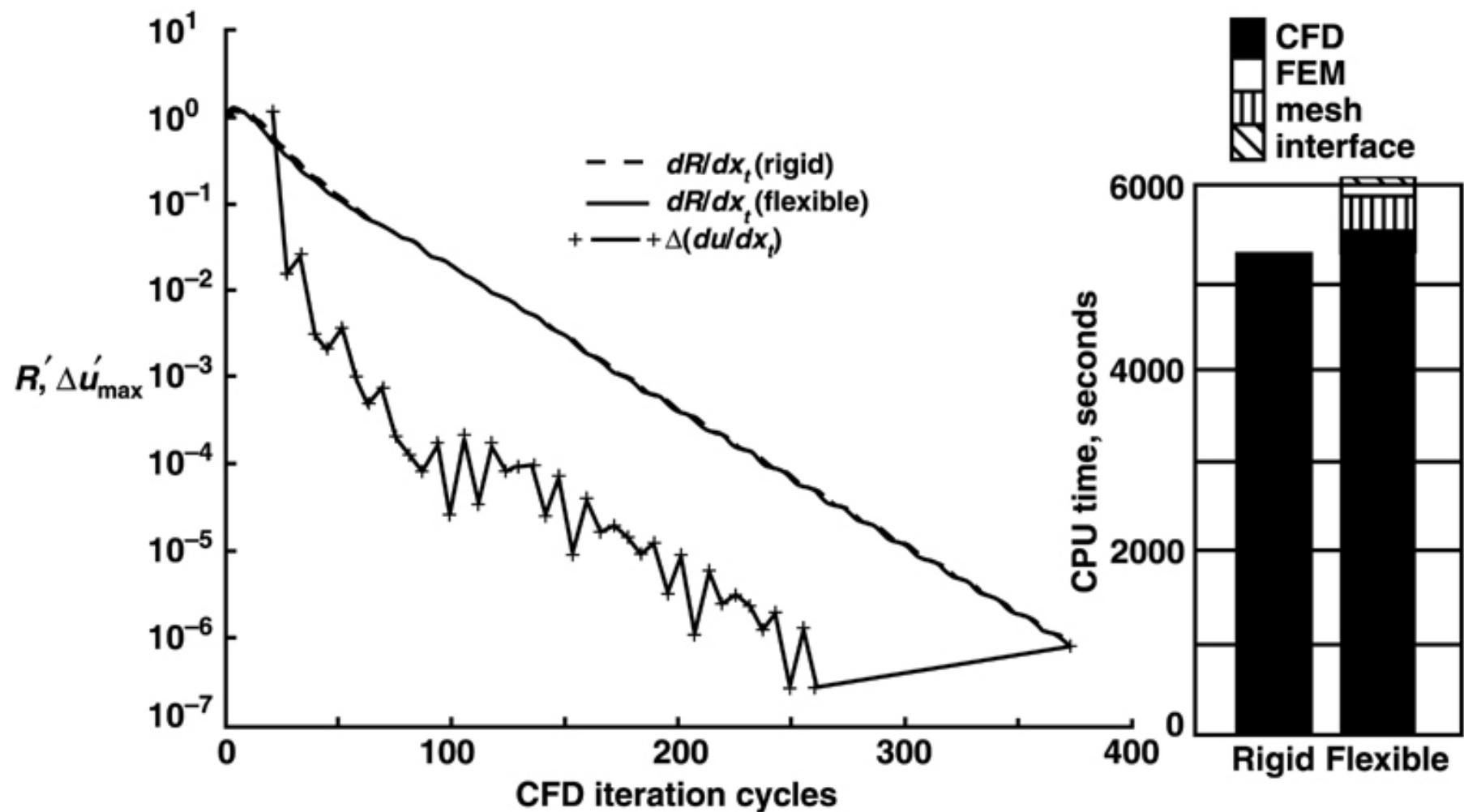
**73x25x25**  
**CFD mesh**  
**(flexible wing)**



**FEM mesh**  
**subset of CFD mesh**  
**583 points**  
**3251 elements**

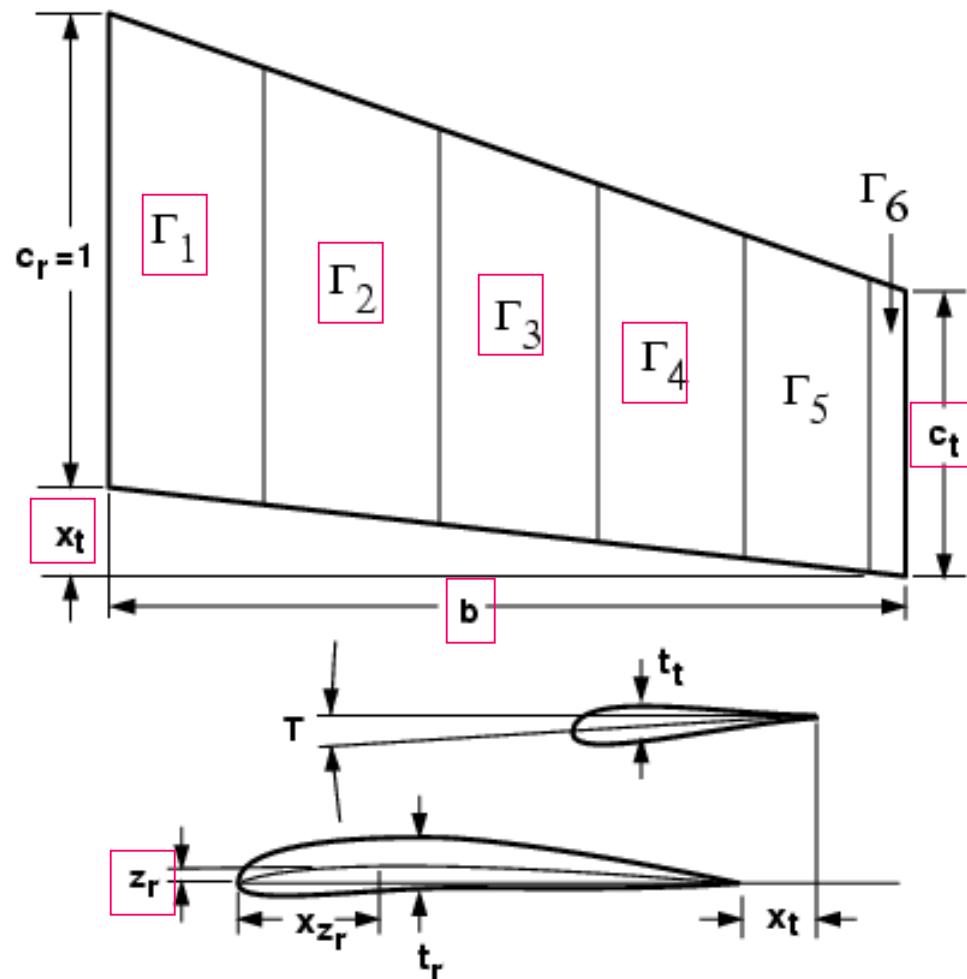


# Process Implementation Aerodynamics / Structures Derivative Coupling



# Application Problem

## Wing Configuration and Parameterization



- 5 planform variables
- 10 airfoil shape variables
  - 5 per section
- 6 structure sizing coefficients
  - Predefined relative size of skin, spar, and rib elements

# Application Problems

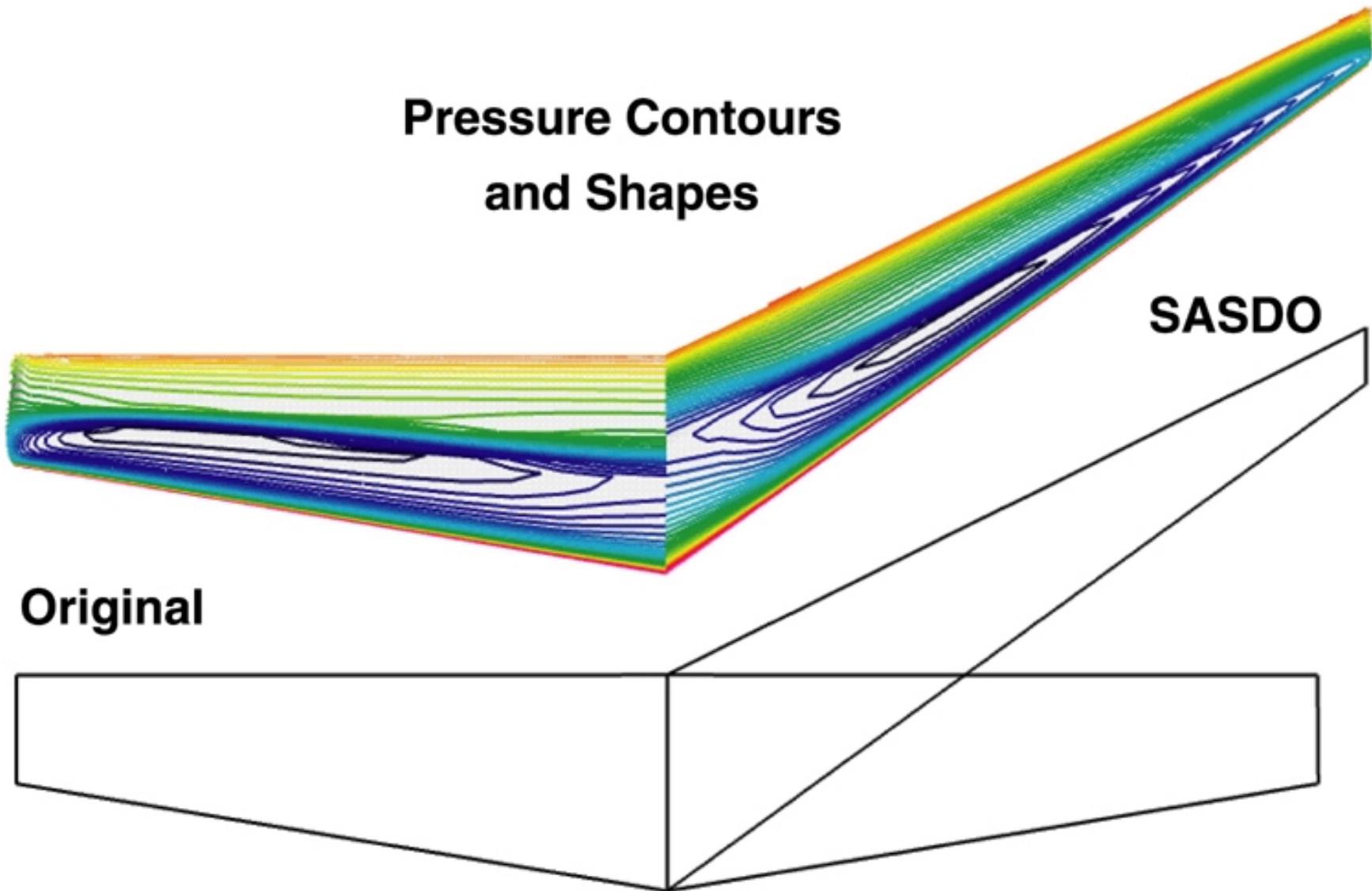
## Optimization of a 3D wing

- Objective function: negative lift to drag ratio,  $-L/D$
- Constraints:
  - minimum payload:  $C_L S q_\infty - W \geq L_{min}$
  - maximum compliance:  $\oint p^r u_g ds^r \leq P_{min}$
  - maximum pitching moment:  $C_m \leq C_{m_{max}}$
  - minimum leading edge radius: enforced by geometry module
- Design variables: planform, section, and sizing

# Eight-Design-Variable Results

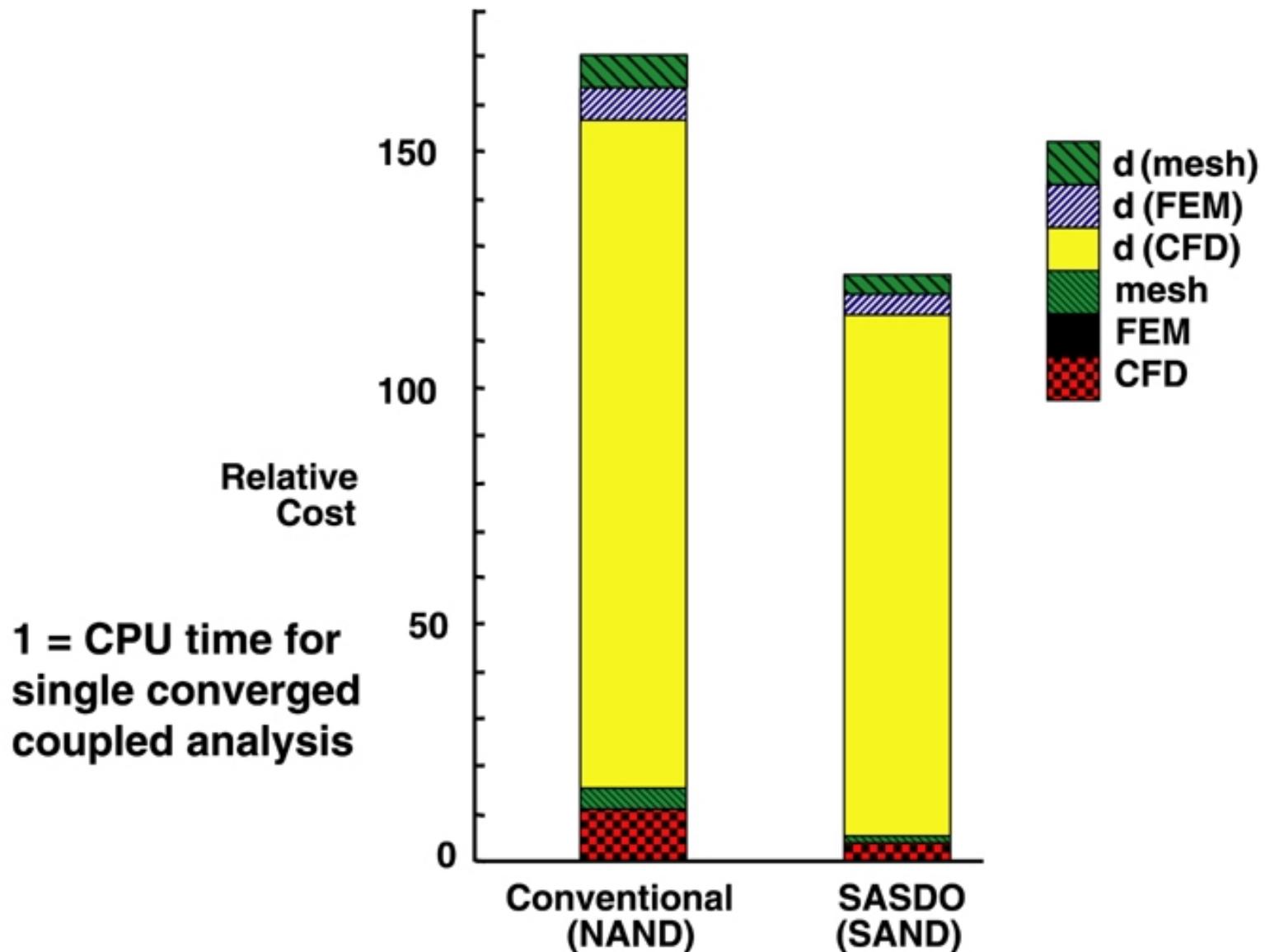
$M_\infty = 0.8, \alpha = 1^\circ$

Pressure Contours  
and Shapes



# Eight-Design-Variable Results

## Computation Cost



# Conclusions

- Initial 3-D wing results obtained for shape and sizing optimization
- SASDO finds the same or similar local minimum as conventional technique
- SASDO requires few modifications to the function and sensitivity analysis codes
- SASDO can be more computationally efficient than conventional gradient-based techniques
- Gradient computation times dominate SASDO

# Future Work

- Gradient cost
  - adjoint approach for loosely coupled analyses
  - code (compiler) optimization for AD code
  - other approximations or methods
- Optimizer control
- Sensitivity analyses error control
- Generalize aero/struct coupling
- Nonlinear structural analysis
- Nacelle design application
- Use state and sensitivity analysis module for uncertainty propagation

# SASDO References

Hou, G. J. -W., Taylor, III, A. C., Mani, S. V., and Newman, P. A.: "Simultaneous Aerodynamic Analysis and Design Optimization," Abstracts from 2<sup>nd</sup> U.S. National Congress on Computational Mechanics, Washington, DC, Aug., 1993, pp. 130.

Hou, G. J. -W., Korivi, V. M., Taylor, III, A. C., Maroju, V., and Newman, P. A.: "Simultaneous Aerodynamic Analysis and Design Optimization (SAADO) of a Turbulent Transonic Airfoil Using a Navier-Stokes Code With Automatic Differentiation (ADIFOR)," Computational Aerosciences Workshop 95, edited by W. J. Feiereisen, and A. K. Lacer, NASA CD CP-20010, Jan. 1996, pp. 82-85.

Gumbert, C. R., Hou, G. J. -W., and Newman, P. A.: "Simultaneous Aerodynamic Analysis and Design Optimization (SAADO) of a 3-D Rigid Wing", Proceedings, 14<sup>th</sup> AIAA Computational Fluid Dynamics Conference, Norfolk, June 1999;also AIAA Paper 99-3296.

Gumbert, C. R., Hou, G. J. -W., and Newman, P. A.: "Simultaneous Aerodynamic Analysis and Design Optimization (SAADO) of a 3-D Flexible Wing", AIAA Paper 2001-1107, January 2001.

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